

**INTO THE MIRE: THE BEHAVIOR OF FINES IN A MUD OCEAN ON CERES AND OTHER CARBONACEOUS BODIES.** K. M. Cannon<sup>1</sup> and D. T. Britt<sup>1</sup>, <sup>1</sup>University of Central Florida, Department of Physics, Orlando, FL 32816. Email: [cannon@ucf.edu](mailto:cannon@ucf.edu)

**Introduction:** Results from the *Dawn* mission suggest the planet Ceres is at least partially differentiated, with a carbon-rich crust made of clays, salts, clathrates and ice [1-3]. Thermal evolution models based on muddy oceans have been used to understand the interior evolution of Ceres [4-5], but there are other alternatives [6]. A key question is whether silicate fines would actually stay suspended as mud in a subsurface ocean before it froze, or whether they would agglomerate and sink.

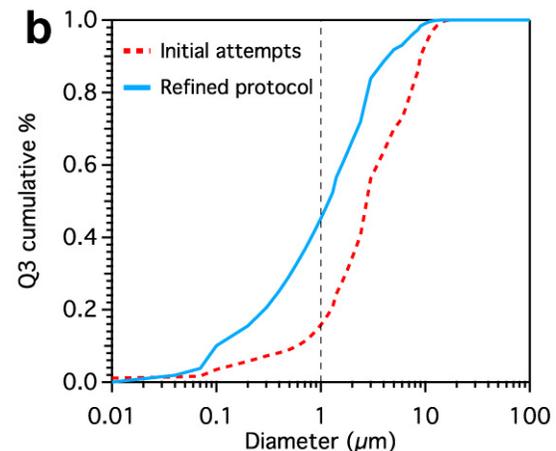
If Ceres and other similar carbonaceous bodies accreted from a mix of ice, chondrules and fines, then the very early stages of ice melting should have caused embedded fines to sink, unless: (1) fines formed a stable colloidal dispersion and remained suspended indefinitely, as has been assumed in thermal models; or (2) convective or other turbulent forces were strong enough from the very beginning to counteract the gravitational settling of aggregates, or later convective forces were strong enough to shear particles off the ocean bottom and re-entrain them. Here we specifically examine (1) using a set of laboratory experiments.

**Materials and Methods:** We prepared micron-sized mineral fines using a RETSCH® PM100 Planetary Ball Mill. Milling was performed using zirconia-lined grinding jars and 3 mm zirconia media, and particle size distributions were measured using a Cilas 1190 particle size analyzer (Fig. 1). Based on the elemental composition of CM and CI chondrite matrices, we backed out an anhydrous “precursor” mineralogy meant to represent the initial accreted fines that eventually became chondritic matrix (Table 1). The milled minerals were mixed in the appropriate ratio, and to test progressive aqueous alteration we can mix increasing amounts of micron-sized serpentine with this anhydrous mixture.

Table 1. Phase proportions in anhydrous mix.

Phase	Proportion (wt.%)
Olivine	32.0
Pyroxene	27.4
Pyrrhotite	19.1
Amorphous Silicate	9.5
Sub-bituminous Coal	7.0
Iron metal	5.1

We performed two sets of initial experiments to examine mud formation and stability: slowly melting mixtures of ice and silicate fines at different ice:rock ratios, and stability of fines in different fluid conditions.

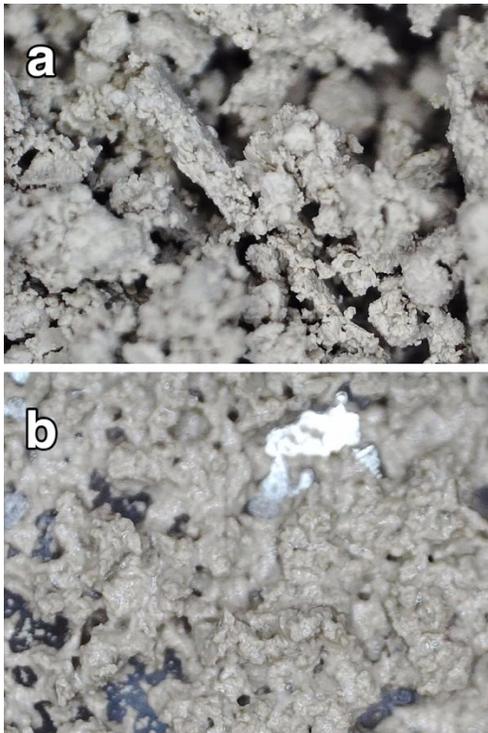


**Figure 1.** a) Micron-sized olivine after grinding, with embedded zirconia media. b) Particle-size distribution of olivine fines, showing initial attempts and refined milling procedures.

For the stability experiments, the silicate fines were combined with water to form a colloidal dispersion with a filling factor ( $V_{\text{solid}}/(V_{\text{solid}}+V_{\text{liquid}})$ ) of approximately 0.05 in order to avoid non-Newtonian behavior that occurs at higher values. The resulting dispersions were physically agitated to produce a homogeneous fluid, then poured into a graduated cylinder. Many different variables affect colloidal stability: mineralogy, fluid pH, salt content, etc. So far our experiments have examined pH (using values of 4.0, 7.0 and 10.0), dissolved salt content (using  $\text{NaCO}_3$ ), and a 50-50 combination of the anhydrous mix and serpentine. Stability is easily gauged by eye, and for unstable dispersions the sedimentation rate can be calculated using video.

**Results:** Preliminary melting experiments show an interesting dichotomy: at low ice:rock ratios ( $\sim 0.4$  by mass), upon melting the mixture of ice and fines maintains porosity and forms a soft solid (Fig. 2a). At higher ice fractions, the pore spaces collapse completely to form a mud (Fig. 2b). More work will be done to test further ice:rock ratios, the effects of initial compaction, and to scale up these experiments to the point where the material at the bottom is compressed by the weight of the column.

In the initial stability experiments, all the dispersions tested so far have been highly unstable, almost immediately forming aggregates that settled out within a matter of minutes. The variables tested to date (pH, salt, serpentine) did not have a measureable effect, although the trial with serpentine took much longer to settle (but not to aggregate), likely due to its lower grain density.

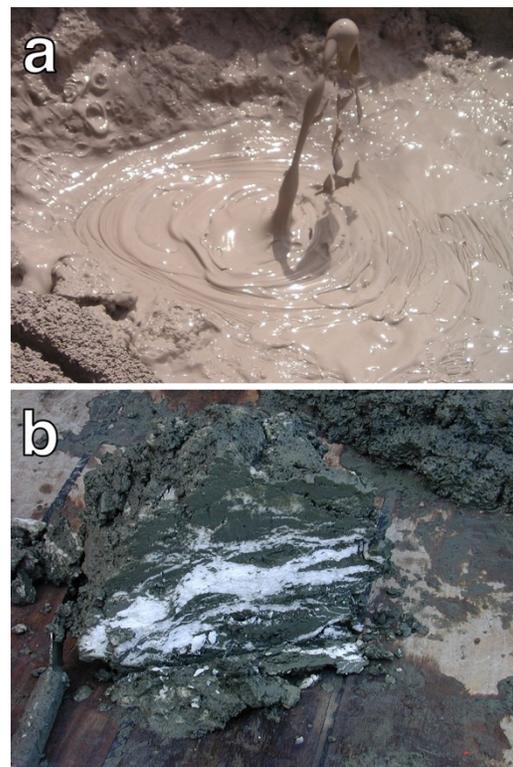


**Figure 2.** Melting experiments at low (a) and high (b) ice:rock ratios.

**Discussion and Future Work:** The stability experiments completed so far suggest it is difficult to suspend colloidal-sized silicate fines in a subsurface ocean on long timescales. Of course the settling rates of aggregates will be slower on Ceres than in terrestrial gravity, but this difference is trivial on geologic timescales. It is possible there are conditions that will lead to stable dispersions; more experiments will be conducted to explore this possibility. However, at this point it seems

that fines may have a natural tendency to sink in a carbonaceous ocean. There are forces that could counteract this tendency: namely, convection. But it seems unlikely that vigorous convection could start up in an initially frozen body before the fines settled. Particles could be re-entrained once settled, depending on the bottom shear stress.

If fines are not stable under any conditions, and cannot be re-entrained by convection in an overlying ocean, then the Cerean crust likely represents the exposed ocean floor after an overlying ice shell was sublimated away, as suggested by [7]. In this case, interior evolution is probably better understood by analogy to seafloor sediments (Fig. 3b) rather than mud pots (Fig. 3a).



**Figure 3.** “Mudball” type models for Ceres assume a warm convecting mud (a), but based on the difficulties of keeping fines suspended, a more apt analogy may be clathrate-ridden seafloor sediments (b).

**References:** [1] Marchi S. et al. (2018) *Nature Astron.* [2] Fu R. R. et al. (2017) *EPSL*, 476, 153-164. [3] Ermakov A. I. et al. (2017) *JGR*, 122, 2267-2293. [4] Neveu M. and Desch S. J. (2015) *GRL*, 42, 10,197-10,206. [5] Travis B. J. et al. (2018) *MAPS*, 53, 2008-2032. [6] King S. D. et al. (2018) *LPSC XLIX*, Abstract #2273. [7] Castillo-Rogez J. C. et al. (2016) *LPSC XLVII*, Abstract #3012.